Materials and Design 111 (2016) 88–97

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Evaluation of pavement responses and performance with thermal modified asphalt mixture

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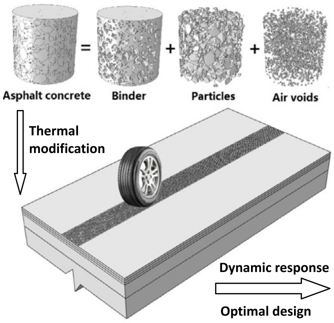
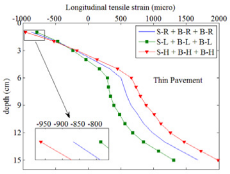
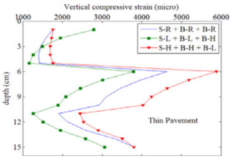
HIGHLIGHTS

- Finite element modeling and mechanistic-empirical analysis are used to analyze pavement responses and performance
- Using combination of low- and high-conductivity asphalt mixtures can improve asphalt pavement performance
- Effect of thermal modified asphalt mixture is more significant on the thinner asphalt layer or at high temperature

GRAPHICAL ABSTRACT







ARTICLE INFO

Article history:
Received 24 May 2016
Received in revised form 27 August 2016
Accepted 29 August 2016
Available online 31 August 2016

Keywords:
Asphalt pavement
Thermal properties
Finite element analysis
Rutting
Fatigue cracking

ABSTRACT

The thermal properties of asphalt mixture play an important role in determining asphalt pavement temperature and accordingly viscoelastic pavement responses under vehicular loading. This paper aims to quantify the effect of thermal modified asphalt mixture on pavement responses and performance. A validated microstructure model of asphalt mixture was developed to predict thermal properties of asphalt mixtures with different thermal additives. The three-dimensional (3-D) finite element (FE) models were developed to predict temperature fields in the pavement structure and critical pavement responses under vehicular loading. The accuracy of the 3-D FE model was validated with field measurements. The critical responses in different thermal-modified pavement structures were analyzed. The long-term pavement performance including rutting and fatigue cracking were evaluated using the mechanistic-empirical analysis procedure. The analysis results show that using low-conductivity asphalt mixture in the surface course and high-conductivity asphalt mixture in the deeper layer decreased rutting effectively at high temperature and moderate temperature, but increased rutting slightly at low temperature. Using low-conductivity asphalt mixture in the pavement, especially in the upper layers could effectively improve the resistance to fatigue cracking at high temperature and moderate temperature, but slightly decrease the fatigue cracking resistance at low temperature. Finally, thermal-modified pavement structures that can improve both rutting and fatigue cracking resistance effectively were recommended.

1. Introduction

The mechanical behavior of asphalt mixture is highly temperature dependent since it is a viscoelastic material. Therefore the pavement

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http://dx.doi.org/10.1016/j.matdes.2016.08.085
0264-1275/

temperature fields have important influences on pavement responses and long-term performance of asphalt pavement under moving vehicular loading [1]. Since thermal properties of asphalt concrete affect heat transfer in the asphalt pavement structure, it is possible to change pavement temperature fields and improve pavement performance by modifying thermal properties of asphalt mixtures.

Recent studies show that the thermal properties of asphalt mixture can be modified by adding a small percentage of conductive or insulation fillers or replacing coarse aggregate with lightweight aggregate [2,3,4,5]. The impact of thermal properties of asphalt mixture on temperature profile in the pavement and pavement surface temperature has been studied [6,7,8]. It is expected that changing pavement temperature fields will affect viscoelastic responses of asphalt pavements such as tension and compressive strains and thus pavement rutting (permanent deformation) and fatigue cracking potential [9]. However, at present, few studies have been conducted to study the performance change of thermal modified asphalt pavements considering the interaction of material selection and structure design. Although pavement responses under moving vehicular loading have been studied for different pavement structures, the evaluation of pavement performance using different thermal modified asphalt mixtures were not well studied.

2. Objective

This paper aims to quantify the effect of thermal properties of asphalt mixture on viscoelastic pavement responses and pavement life. The microstructure model of asphalt mixture was developed to predict thermal properties of asphalt mixtures under different heat boundary conditions. A series of pavement structures were designed using different layer combinations of thermal modified asphalt mixtures. The three-dimensional (3-D) finite element (FE) models were developed and validated to predict temperature fields in the pavement structure and accordingly critical pavement responses under vehicular loading. The long-term pavement performance including rutting and fatigue cracking potential were evaluated using the mechanistic-empirical pavement analysis approach. The pavement structures which effectively improve both rutting and fatigue cracking resistance were recommended.

3. Evaluation of thermal properties of asphalt mixture

3.1. Generation of asphalt mixture microstructure

Compared with the indoor experiment, virtual tests provide a convenient way to determine the material properties of asphalt mixture [10,11]. Thermal properties of asphalt mixtures have been evaluated through a multi-scale virtual testing developed in the authors' previous work, which has been validated with experimental measurements [12]. Since cylinder specimens are commonly used in asphalt mixture experiments, 3-D heterogeneous microstructures of cylinder specimens containing mineral aggregates, asphalt binder, air voids, and conductive or insulation fillers (graphite power or ceramic particles) were generated. Fig. 1(a) shows an example of the generated heterogeneous microstructures. The asphalt mixture can be divided into three parts, including continuous asphalt matrix, mineral aggregates, and air voids, as shown in Fig.1(b)–(d). The 3-D heterogeneous cylinder specimens were imported into commercial FE software ABAQUS for future thermal analysis.

The multi-scale modeling approach is used to alleviate the difficulty that the full-size asphalt mixture specimen contains too many aggregates. Aggregate particles that were smaller than 2.36 mm were grouped as the fine aggregate matrix (FAM). For these aggregates, different sized heterogeneous cylinder specimens were generated one by one from the smallest size. Aggregates larger than 2.36 mm were treated as the coarse aggregates, which were generated in the microstructure together with the FAM. In this multi-scale approach, the microstructure composed of the smaller aggregates was regarded as the matrix of the next microstructure composed of larger aggregates. The thermal properties of the asphalt mixture can be calculated step by step from the smallest heterogeneous cylinder. The sizes of different cylinders were shown in Table 1.

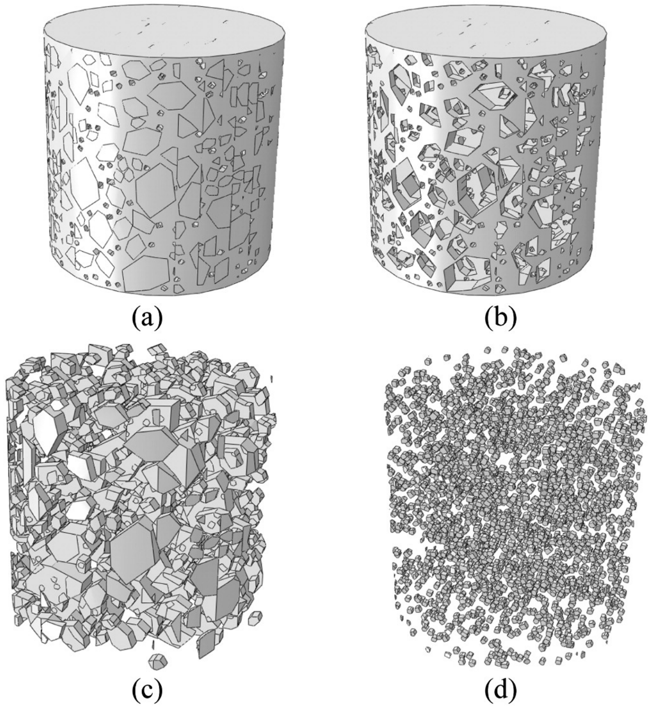

Fig. 1. Illustration of 3-D microstructure for (a) asphalt concrete, (b) asphalt matrix, (c) mineral aggregates and (d) air voids.

In this study, graphite powders and ceramic particles were used as the conductive and insulation fillers respectively. When generating the heterogeneous cylinders, since the sizes of graphite powders were smaller than 0.15 mm [4], they were used to replace fine aggregates with sizes between 0.075 mm and 0.15 mm. The sizes of ceramic particles were larger than 2.36 mm [8] and therefore they were used to replace coarse aggregates.

3.2. Heat transfer models

Thermal properties of asphalt mixtures include thermal conductivity, specific heat capacity, and thermal diffusivity. A series of heat transfer modes as shown in Fig. 2 were applied to the virtual testing specimens to calculate the above thermal properties.

A steady heat transfer process shown in Fig.2(a) was used to calculate the thermal conductivity. The top surface temperature and bottom surface temperature of the cylinder were kept to be T_1 and T_2, respectively. Based on the Fourier's law, for a homogenous cylinder, the

Table 1
Sizes of cylinder specimens used in the simulation at different scales.

Aggregate size (mm)	Cylinder diameter (mm)	Cylinder height (mm)
<0.075	1.5	1.5
0.075–0.15	3	3
0.15–0.3	6	6
0.3–0.6	12	12
0.6–1.18	25	25
1.18–2.36	50	50
>2.36	100	100